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Multiple Access in Ultra-Wideband Communications Using Multiple Pulses (U)

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ABSTRACT

Multiple access (MA) in UWB communication is an area of active research. To date several time-division or code-division pulse amplitude modulation (PAM) or pulse position modulation (PPM) schemes have been proposed to separate multiple users in UWB communications. Conventionally, all users employ the same pulse shape and modulate the transmit pulse based on changing amplitude or position. One concern with using the same pulse for all channels is that the multiple access interference (MAI) increases as the number of users increase. This is due to increased cross-correlation between similar pulses of the different channels, raising thus the noise floor in such systems. In this paper we introduce and study the performance of a new MA scheme in the context of multiple orthogonal transmitted-reference (T-R) short duration (nsec) chirp pulses in the presence of multipath and additive white Gaussian noise (AWGN).

1. INTRODUCTION

Ultra-wideband communication systems modulate short duration (picosec to nanosec) pulses to transmit and receive information. The pulses used in such systems have bandwidths of GHz range and a fractional bandwidth larger than 20% [1]. Fractional bandwidth is defined as

$$B_f = \frac{2(f_h - f_l)}{f_h + f_l}.100\% \qquad (1)$$

Where f_h, and f_l are the highest and lowest cut-off frequency (-10 dB point) of a UWB pulse spectrum respectively. The large bandwidth of UWB signals provide robustness to jamming and have low probability of detection properties. UWB devices usually require low transmit power due to control over duty cycle, thus allowing longer battery life of handheld equipments. These features can make UWB systems a good candidate for reliable wireless data communications between different devices in a spacecraft. For multiple wireless devices communicating in a spacecraft, proper multiple access techniques are needed for channelization of multiple users. In a multiple access UWB communications system, users transmit information independently and concurrently over a shared channel. The received signal is therefore a superposition of all user signals with added channel noise. There has been extensive research in separating multiple users in a multiple access UWB system using TDMA or CDMA Pulse Amplitude Modulation (PAM) and Pulse Position Modulation (PPM) techniques [3,4, 5, and 6]. PAM modulation encodes the data bits based on the amplitude change in short duration UWB pulses. Therefore, received pulses are decoded based on their amplitude levels. This modulation technique is highly susceptible to noise and false pulses can be detected in multipath channels. In PPM modulation, signals are encoded based on the position of transmitted pulse trains by shifting the pulses in a predefined window in time. PPM transmitted signals are usually demodulated and recovered with autocorrelation techniques. However, the limitation of this modulation method is that by modulating the position of pulses, the system becomes more complex and also multiple access interference (MAI) increases as the number of users increase. To overcome high cross-correlation between similar pulses, Ghavami and Kohono in [9] have suggested the pulse shaping modulation using Hermite-based orthogonal pulses. Using multiple pulses with low cross-correlation in multiple access systems reduces the MAI effect that arises between several users.

In this paper we extend the previous work on UWB delay modulation technique [7] and transmitted-reference (TR) receivers [8] by using multiple orthogonal pulses. Authors of [7,8] proposed to use a symbol that consists of a pair of pulses (doublets) separated by a unique delay to represent each bit. The first pulse is fixed and the second pulse is modulated by data using opposite polarities to represent one or zero. This method has the advantage of sending the same pulse twice through an unknown channel where both pulses are distorted the same way and detection becomes easier with an autocorrelation receiver. However their method uses a single UWB pulse shape for all users. The scheme proposed in this paper uses multiple orthogonal pulses for a UWB system and is a step towards combining the multi-pulse approach and T-R modulation in a multiple access ultra wideband (MA-UWB) communications system. This study investigates the performance of a multiple-pulse multiple-delay (MPMD) modulation scheme that exploits most of the energy in the autocorrelation function of orthogonal

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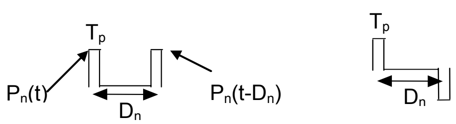
pulses. The pulses used in this paper are mutually orthogonal chirp pulses. Chirp signals perform well in the presence of fading due to multipath and have been used in high frequency data transmission applications extensively [11].

Section 2 describes the general UWB signal model, transmitter design and MPMD modulation scheme. Section 3 describes the receiver design and its demodulation technique. Section 4 provides a comprehensive analysis of BER performance of the UWB muti-pulse, multi-delay receiver followed by conclusions in section 5.

2. GENERAL SIGNAL MODEL & TRANSMITTER DESIGN

In this model the transmitted bits are represented by symbols that consist of a pair of short duration (nanosecond) UWB pulses (mutually orthogonal for different users) with a unique separation between them for various channels. The symbols start with a fixed reference pulse (ref) followed by a delay (D) and a modulated data pulse (data). The data pulse modulation scheme is based on the polarity of reference pulse. For example a "1" is symbolized by a reference and a data pulse of the same polarity, while a "0" is represented by a data pulse opposite in polarity with reference pulse. Fig. 1 illustrates the data pulse modulation scheme.



(a) (b)

Figure 1: UWB Pulse Modulation
(a) Symbol for "1" = $P_n(t) + P_n(t\text{-}D_n)$
(b) Symbol for "0" = $P_n(t) - P_n(t\text{-}D_n)$

Here $P_n(t)$ represents a UWB pulse, T_p denotes the UWB pulse width that is the same for all users and D_n represents the delay between pulses. Assuming a uniform symbol period, the general signal model of a UWB multiple access with N users using this modulation technique can be expressed as

$$S_{n,m}(t) = \sum_{n=1}^{N}\sum_{m=1}^{M}\sqrt{E_{p,n}}\,[P_n(t-(m-1)T-(-1)^{b_m^{(n)}}.P_n(t-(m-1)T-D_n)] \quad (2)$$

Where

N = Number of users
M = Number of transmitted bits
$E_{p,n}$ = n^{th} user's signal energy (normalized for all users)
$P_n(t)$ = n^{th} user's UWB pulse
$b_m^{(n)} = [b_1^{(n)}, \ldots, b_M^{(n)}]$ n^{th} user's m^{th} data bit, $b_m^{(n)} \in [0,1]$
D_n = n^{th} user's delay
T = Pulse repetition period

The UWB pulses used in this work are short duration chirp pulses with different start and end frequencies. Chirp pulses that do not overlap in frequency band are theoretically uncorrelated with each other. Therefore, these pulses can be separated using autocorrelation technique shown below.

$$S(t) = S_1(t) + S_2(t) + \ldots + S_N(t) \quad (3)$$

$$S_1(t).S(t) = \underbrace{S_1(t).S_1(t)}_{\delta(t)} + \underbrace{\cancel{S_1(t).S_2(t)}}_{0} + \ldots + \underbrace{\cancel{S_1(t).S_N(t)}}_{0} \quad (4)$$

3. RECEIVER DESIGN

The receiver in MPMD technique takes advantage of the fact that the shape of autocorrelation functions (ACF) of UWB pulses are preserved at the receiver. While the shape of pulses can dramatically be distorted based on various channel distortions such as multipath, fading and thermal noise. Fig. 2 illustrates this point

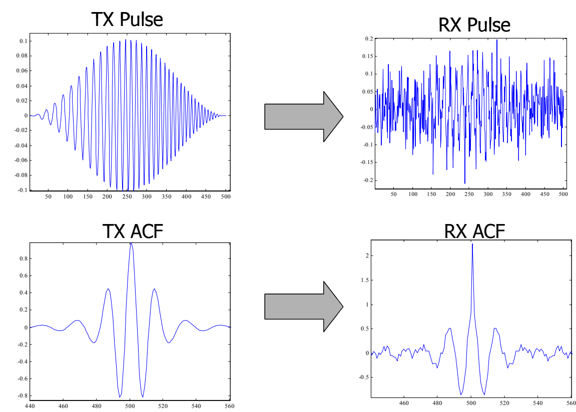


Figure 2: Channel Degradation Effect on a Pulse and it's ACF

Most pulses used in UWB communication systems have ACFs with strong side lobes (non-zero lags). The information stored in the non-zero lags are available for free in a multiple pulse system. Therefore, sampling the *non-zero* lags can provide considerable performance improvement to the pulse detection systems. The proposed UWB receiver samples the receiver autocorrelation function at both *zero*- and *non-zero* lags, thus sampling and matching the shape of ACFs rather than just the shape of the received pulses. Sampling of non-zero ACF lags is a significant new approach that has shown improved bit error rate performance over a conventional *zero-lag* receiver (i.e. energy detection receiver). The input signal to the proposed MPMD receiver is given by

$$R_{n,m}(t) = S_{n,m}(t) + w(t) \quad (5)$$

Where $S_{n,m}(t)$ is the combined signal for N users and M bits from (2) and $w(t)$ is AWGN with zero mean and two-sided power spectral density $N_0/2$.

The MPMD demodulation scheme has two steps. Step one provides estimates for multiple sampled values of the received signal's ACF. These estimates are achieved from multiplying the received signal by its multiple delayed versions. The second step involves matching the estimated values from previous step to the sampled values of ACFs for each users pulse. Fig. 3 represents the multi-pulse multi-delay receiver block diagram.

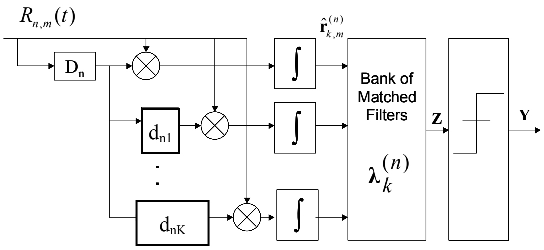
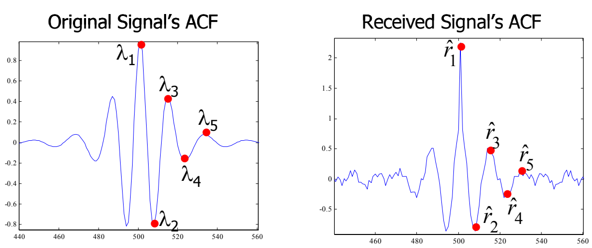


Figure 3: MPMD Receiver Block Diagram

As shown in Fig.3 the receiver employs autocorrelation technique by multiplying the received signal with multiple delayed versions of itself and integrating over a finite time. Then a bank of matched filters containing ACF samples for each user ($\boldsymbol{\lambda}^{(n)}_k$) followed by a hard decision block separates each channel. Note that D_n and d_n are unique for each receiver channel. Fig. 4, shows the matching of original and received pulses ACF samples.



$\mathbf{Z}=\boldsymbol{\lambda}^{(n)T}_k.\hat{\mathbf{r}}^{(n)}_{k,m}$ Where: n=1, 2, …, N (# of users)
k=1,2,…,K (# of lags)
m=1,2,…,M (# of bits)

Figure 4: Matching the Shape of ACFs of a Received and Transmitted Pulse

The output of the receiver is

$$\mathbf{Y} = \mathrm{sgn}(\underbrace{\boldsymbol{\lambda}^{(n)}_k.\hat{\mathbf{r}}^{(n)}_{k,m}}_{\mathbf{Z}}) \tag{6}$$

Where

$$\boldsymbol{\lambda}^{(n)}_k = \left[R^{(n)}_{p_n p_n}(1) \quad . \quad . \quad . \quad R^{(n)}_{p_n p_n}(K) \right] \tag{7}$$

$$\hat{\mathbf{r}}^{(n)}_{k,m} = \begin{bmatrix} \hat{r}^{(n)}_{(1,1)} & . & . & . & \hat{r}^{(n)}_{(1,m)} \\ . & . & & & . \\ . & & . & & . \\ . & & & . & . \\ \hat{r}^{(n)}_{(K,1)} & . & . & . & \hat{r}^{(n)}_{(K,m)} \end{bmatrix} \tag{8}$$

$\boldsymbol{\lambda}^{(n)}_k$ denotes the normalized autocorrelation vector of n^{th} user's pulse for K sampling points (lags) and $\hat{\mathbf{r}}^{(n)}_{k,m}$ is the autocorrelation matrix of n^{th} user's m^{th} bit for K lags. Each row of the matrix in (8) represents the autocorrelation between the received signal and its delayed version based on different delays as shown in (9).

$$\hat{r}^{n}_{k,m} = \int S_n(t).S_n(t-\Delta_n)dt \tag{9}$$

Where Δ_n is the total delay as

$$\Delta_n = D_n + d_{nk} \tag{10}$$

D_n represents the n^{th} users main delay that provides lag *zero* in the ACF, and d_{nk} denotes the offset from its main delay or lag k in autocorrelation. Delaying the received signal by D_n causes the "ref" pulse to align with the "data" pulse in each symbol and their product decodes the symbols for received data bits by capturing the energy in lag *zero* of the generated autocorrelation function. Further delaying the received signal by multiple offsets (d_{nk}) added to the main delay (D_n) and multiplying with its un-delayed version, samples the autocorrelation function in *non-zero* lags. The sampled points are estimates of the received signals' ACF. These estimated values ($\hat{\mathbf{r}}^{(n)}_{k,m}$) are then matched to the original pulses sampled values of autocorrelation function ($\boldsymbol{\lambda}^{(n)}_k$) and provide a more accurate decoding of the received symbols. Since different pulses are uncorrelated, it is important to overlap a specific users' "ref" pulse with the received signals' "data" pulse to achieve maximum autocorrelation. This results in more reliable signal detection in noisy environments. For this reason, the interference of other users "ref" pulse to the user of interest's "ref" pulse is removed by Gram-Schmidt Process to preserve the shape of the original "ref" pulses used for each channel.

4. PERFORMANCE ANALYSIS

The performance of the proposed system is analyzed based on multiple delays and multiple autocorrelation sampling points. All bit error rate simulations in this section were carried out with total number of 100,000 bits per data point. Fig. 5 illustrates the BER versus SNR for different delay separations between ten users in various SNR levels.

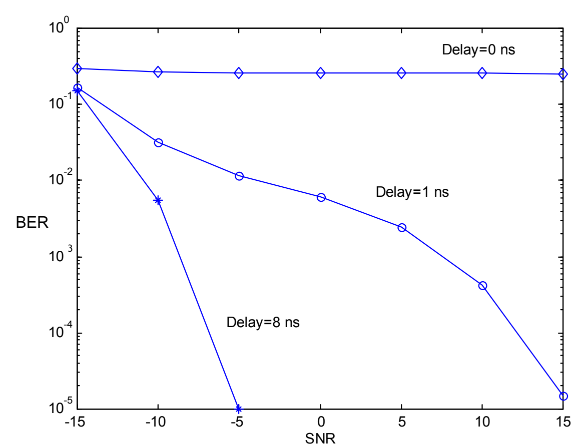


Figure 5: BER versus SNR based on delay separation between users for a 10 user system with 1 lag (k=1)

As shown in Fig.5 the worst BER occurs when there is no separation between the users. However, it is shown that with minimal separation between users the BER performance can improve considerably. Fig.6 represents the performance improvement by increasing the number of sampling points (lags) in the received signal's ACF. Higher number of sampling points in ACF of the received signal provides more accuracy in the match filtering process and results in BER improvements of the system.

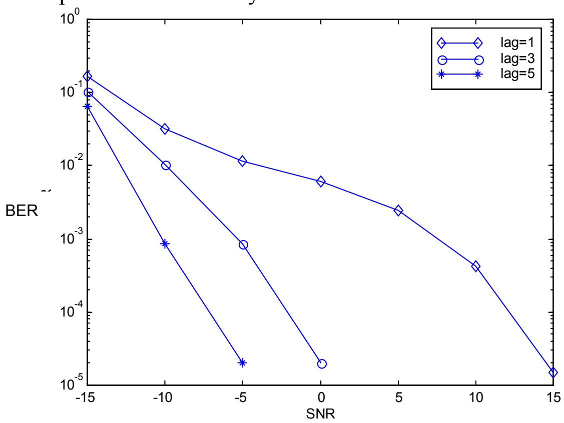


Figure 6: BER Versus Autocorrelation Sampling Points *(K)* for 10 Users at with 1ns Separation Between Users

The results from Fig.5 and 6, show that channel capacity can be increased significantly compared to the time hopping modulations or other techniques that require a large delay between different users. This modulation scheme also is very effective in multipath environments. Since the same pulse is sent twice through a channel where both pulses are distorted the same way by multipath. Therefore the autocorrelation of the distorted "ref" pulse and distorted "data" pulse can still recover the transmitted signal. Fig. 7 compares the BER performance of the proposed receiver in multipath and AWGN channels.

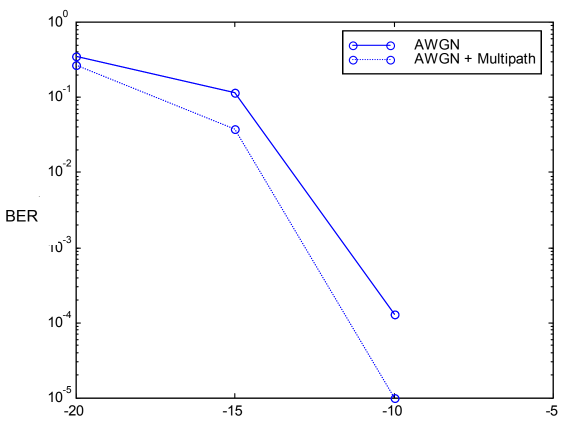


Figure 7: BER Versus SNR for 2 users with 1 ns separation at k=1 in multipath and AWGN channels.

The preliminary results shown in Fig. 7 indicate that performance for multipath outperforms the non-multipath case for a limited set of experiments we have completed. This is because the "ref" pulse and "data" pulse are correlated to each other, and the multipath channel introduces a longer duration in the signal component of the received signal, thus increasing the SNR at the output of the integrator. It is important to note that in order to have high performance in multipath channels, the pulses should be designed to be as orthogonal as possible with respect to shift. Otherwise, orthogonality may not be maintained with multipath and might result in lower performance.

5. CONCLUSIONS

(1) Since UWB occupies a large bandwidth that needs to be shared among multiple users, the MA is an important unsolved problem for a very large number of users. We have introduced an effective MA method which is simple to implement and seems to have excellent BER performance. (2) The analysis reveals that the use of multiple uncorrelated chirp pulses minimizes the MAI and allows the system to increase the transmission rate. The time delays used to separate the users can be a fraction of the pulse duration for each channel providing acceptable BERs. (3) The main contribution of this paper is that the number of sampling points of the autocorrelation function plays an important role to increase the performance of a UWB multiple access system. The results show that the proposed method is efficient as a multiple access UWB technique in high interference environments.

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